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Comparison of heliostat field layout design methodologies and impact on power plant efficiency

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Abstract

The aim of this paper is the presentation of a study of heliostat field layout performances for a CSP plant, based on the central receiver technology, using different algorithms for layout generation. The purpose is to perform a detailed comparison of the layout performances in terms of efficiency and energy yield to determine the algorithms benefits and drawbacks at various scenarios as first step on the optimization of the heliostat layouts designs. The layouts compared are generated using a genetic optimization process and using different objective functions for each studied case. Results show that new biomimetic algorithms are a good alternative to classical algorithm patterns based on the radial staggered method. However, these results are only valid for the analyzed cases.

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Keywords: Solar tower plant; heliostat field layot; optimization

Nomenclature

E_{annual}	Heliostat field annual energy.
$E_{i,annual}$	Annual energy provided by the heliostat i to the receiver.
E_i max	Maximum energy that a heliostat i can provided to the receiver.

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Ib (t)	Beam insolation for the time t.
P(t)	Heliostat field power at the time t.
A_i	Heliostat i mirror area
η	Heliostat field efficiency.
$\eta_{i,t}$	Heliostat i optical efficiency at the time t.

1. Introduction

The heliostat field is a very critical system of a solar tower power plant due to its large impact on the power plant's final efficiency. For this reason, the design of the heliostat field layout is an essential task to be considered in optimization processes. Because of the relative position between heliostats and the positions of the heliostat relative to the tower, losses occur related to cosine effect, shadowing, blocking, atmospheric attenuation and spillage. Several algorithms and methodologies can be found in the literature to design solar field layouts in order to reduce these losses. In addition, these algorithms facilitate the design by reducing the number of parameters to consider. Currently, radial staggered type layouts are used to design real heliostat fields. In specialized literature there are some studies devoted to the assessment of specific algorithms used to create heliostat layouts but up to now, no study has been carried out in order to compare these algorithms under different conditions and for different configurations.

Thus, the aim of this paper is to present a detailed comparison of these algorithms to determine the benefits and drawbacks at various scenarios as a first step on the optimization of heliostat field layout design. Moreover, the methodology used in this paper, could be used to extend the comparison to other scenarios and have a base for optimizing any heliostat field.

The structure of the subsequent sections is as follows, Section 2 describes the algorithms considered in this comparison; Section 3 describes the methodology used for optimizing the heliostat field for the comparison and Section 4 presents the studied case used to compare algorithms and the results of the comparison carried out using the methodology mentioned in the Section 3. Finally, Section 5 summarizes the results and the conclusions obtained in the results section.

2. Heliostat field layouts generation algorithms

The heliostat field layout design is a complex task due to the high computational cost and the high number of variables that has to be taken into account in order to obtain the best heliostat number and their coordinates for a studied case. For the simplification of this hard task, several algorithms have been proposed in the literature. Lipps et al. [1] presents staggered and cornfield configurations, but the conclusion of this work shows that the radial staggered configuration generates more efficient layouts due to the lower losses related to shadowing and blocking.

However, in the last years new algorithms have been published related to biommimetic patterns, these algorithms are inspired in the spiral patterns of phyllotaxis disks. The following subsections describe the algorithms taken into account in the comparison and state why they are considered the most promising ones.

2.1. Dense radial staggered

The radial staggered configuration was originally proposed by the University of Houston for the RCELL code [1]. In these layouts the heliostats are located around a tower in rings. The heliostats of a ring are placed with an azimuth angular spacing and the algorithm ensures that no heliostat is in front of other heliostat of an adjacent row.

Collado et al. [2] presents a simplified version of this algorithm that considers the spacing between the rings of a zone constant. In order to reduce the shadowing and blocking losses, and to keep the minimum distance for mechanical constraints, the algorithm proposed a parameter 'desp' to define the minimum distance between the heliostats.

2.2. Campo

The algorithm in [2] proposes a radial expansion of the dense radial staggered described in the previous subsection. For this algorithm, the first step is the calculation of the parameters that define each of the zones in the field (azimuth spacing, the radius of the first row in the zone, number of heliostats per row and the number of rows in the zone).

Then, for each heliostat a radial expansion is calculated using a blocking factor that is used to calculate how much the radial distance increases.

2.3. Graphical method

The algorithm presented in [3] discusses a methodology to create a radial staggered configuration field using a graphical method that avoids blocking losses between heliostats. The field is also divided in zones in order to increase the land use efficiency.

The methodology defines the radius for a new row selecting the radius that maximizes the land use. For this purpose, the algorithm has to decide whether to add a new row to the current zone or start a new zone when a new ring is needed. In order to add a new row in the zone the radius is trigonometrically calculated. To calculate this radius a line is drawn from the receiver centre point and tangential to the heliostat in the new row and the previous row as can be seen in the Figure 1.

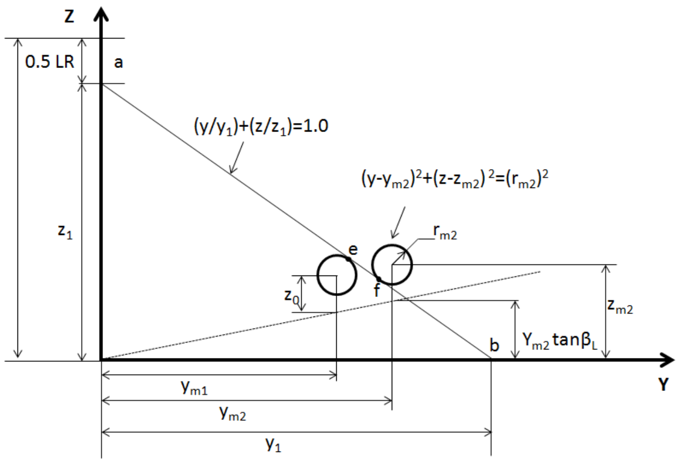

Fig. 1. Scheme used in the graphical method to calculate new row radius.

2.4. DELSOL

The algorithm in DELSOL code and described in [4], divides the field in zones distributed in radial direction and azimuth direction. Then, the azimuth spacing and radial spacing is calculated for this zone using the equations defined in the manual [4]. After verification that this spacing maintains the mechanical limits, the heliostat density is calculated for each zone. Using this information, the number of heliostats per zone can be calculated to define the heliostat positions.

In addition to the pure radial staggered method, DELSOL also includes the option of using "split planes" in order to minimize shadowing and blocking effect. The split plane is a ring in a zone at which the azimuth spacing is changed with respect to its previous value of the zone azimuth spacing. Moving from the center of a zone in radial direction inward towards the tower, adjacent rows become more compressed increasing shadowing and blocking effect. When the errors due to these effects are excessive, some heliostats are removed from a ring in order to alleviate them.

2.5. Fermat spiral.

The Fermat spiral is a pattern used to create biomimetic layouts as proposed in [5].The values of the parameters 'a' and 'b' determine the equations to create the spirals. These equations determine the radial distance to the tower and the azimuth angle in the field. After defining the positions of the heliostats, the algorithm must ensure that these positions respect the limits of security distance. In this algorithm the density of heliostats between zones is more continuous than in radial staggered configurations.

The parameters that each algorithm uses to create a field are different. So, the numbers of values involved in the optimization are different for each algorithm. Table 1 summarizes the parameters involved.

Table 1. Parameters that defines each algorithm.

Algorithm	Parameter	Description
Dense radial staggered	dsep	Security distance for heliostats
Campo	dsep	Security distance for heliostats
	freb	Reference blocking factor
Graphical method	dsep7	Security distance for heliostats
DELSOL	Nrad;	Number of radial zones in the field
	expansionFactor	Expansion factor for fields
	gapBetweenZones	Spacing for rows of different zones
Fermat spiral	a	Parameter 'a' of the Fermat spiral equation
	b	Parameter 'b' of the Fermat spiral equation

3. Heliostat field optimization

For the algorithm comparison it is important to optimize the fields generated with each algorithm to avoid a meaningless comparison. In order words, the comparison of algorithms will be done between the best fields that can be generated by the algorithms. The optimization of the heliostat field layouts is the process to search the best values for the parameters that defines heliostat field algorithms in terms of the objective functions defined below for a search space and taking into account some restrictions.

3.1. Heliostat field generation

In order to search the values of the parameters of the optimized field for a scenario, different heliostat field layouts are generated to simulate them. This section defines the process of the heliostat field generation given the values for the algorithm input parameters.

First, using the algorithm and the input values a large heliostat field is generated. After positioning the heliostats, the field is simulated to calculate the annual energy that each heliostat provides to the receiver. To calculate this energy a simulation program is used that calculates the errors involved in the central receiver energy production: cosine effect, shadowing, blocking and atmospheric attenuation.

After this calculation, the heliostats are sorted according to the annual energy provided and for each heliostat the power at design point is also calculated also by simulation. Considering the ranking of heliostats and their power at design point the final heliostat field is generated taking the first heliostats with the higher annual energy until reaching the design point power.

3.2. Objective function

To accomplish a complete comparison, two essential cases have been studied for each scenario: comparison among the different optimized algorithms in terms of efficiency and construction of a Pareto front generated from the higher performance fields studied. The following subsections define the objective functions used in each studied case.

3.2.1. Field efficiency

The first objective function used to compare the fields is maximizing the field efficiency. This objective function has been selected because heliostat field layouts with low efficiency heliostat are not realistic.

The instantaneous optical efficiency of a heliostat, see equation 1, is used to calculate the annual energy provided by the heliostat to the receiver (equation 2). The annual energy is the adding up of the annual energy of field heliostats. Finally, the heliostat efficiency is calculated as factor between the annual energy provided by the heliostats and the heliostats incident annual energy (equation 3).

$$\eta_{i,t} = \eta_{\cos} \cdot \eta_{shadow} \cdot \eta_{block} \cdot \eta_{att} \tag{1}$$

$$E_{i,annual} = \sum_t A_i \cdot \eta_{i,t} \cdot Ib_t \tag{2}$$

$$\eta = \frac{E_{annual}}{E_{inc-annual}} = \frac{\sum_i E_{i,annual}}{DNI \times \sum_i A_i} \tag{3}$$

$$\max(\eta) \tag{4}$$

3.2.2. Annual energy vs. field efficiency

The ideal field is the one with the highest annual energy and the highest efficiency. In the heliostat field layout design process, it is interesting to generate a field that provides the highest annual energy to the receiver in order to produce the maximum electricity. However, when optimizing taking into account only this issue, the fields obtained will be fields with a large number of heliostats. Thereby, the annual energy objective conflicts with efficient fields because some of the heliostats of these fields could be heliostats with low efficiency. For this reason, a multi-objective optimization process is proposed where it is not possible to obtain an optimum solution for both of them. Instead, in the optimization process a set of solutions can be found with a good compromise between the two objectives. For that, the multi-objetive problem is transformed into a one objective function problem and defining the other objective function as restriction of the problem.

$$\max(E_{annual})$$

$$\textit{with, } \eta \geq \varepsilon \tag{5}$$

Considering equation (5) the optimization can be resolved for different regions for different values of ε. As a result a Pareto front is obtained, the set of optimal solutions.

3.3. The BSA methodology

The classical optimization techniques are able to solve simple problems where the objective functions and restrictions are linearly related. However, this optimization methodologies cannot be applied due the complexity of the problem and, therefore, a heuristic technique is used. The Backtracking Search Optimization Algorithm (BSA) presented in [6] is an evolutionary algorithm. The process for the optimization of this algorithm is the following:

- An initial population is built with randomly generated values for the parameters,

- The objective function/objective functions are evaluated for each individual in the initial population,
- The best individuals are selected taken into account the objective function /objective functions,
- A new population is generated using crossover and mutation operations,
- The evaluation of new individuals are carried out,
- The individuals not selected are replaced with the new individuals,
- Repeat the selection, crossover and mutation, evaluation and replacement of individuals until optimization process is finishes.

The optimization process will be finished when the time limit for optimization is spent, a maximum number of evaluations are carried out or the required accuracy is achieved. The following figure shows the scheme for evolution algorithms.

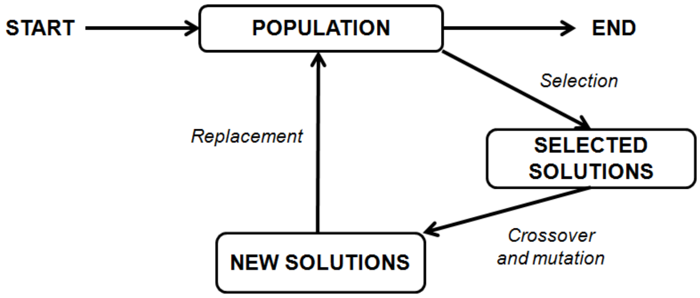

Fig. 2. Evolutionary algorithms scheme.

In this study, the individuals are tuples of values of the input parameters of an algorithm. For each individual a field is generated. Then, these fields are evaluated to select the best fields taken into account the objective function. After the selection, the individuals that have not been selected are replaced for other individuals generated by crossover and mutation operations.

4. Results

For this first comparison of the heliostat field layout generation algorithms, three study cases have been defined. The three cases are surrounding heliostat fields of 120m^2 heliostats located in Seville. For each of the scenarios different power values have been defined for the design point: 100 MWth, 120 MWth and 150 MWth. So in the evaluation, fields that provide these powers at design point are built. The following table defines the scenarios where the algorithms have been compared.

Table 2. Parameters that defines the scenarios for the comparison.

Parameter	Value
Location	37.5º N; 5.3º W Seville (Spain)
Annual DNI	1999 kWh/m^2
Design point day	21st March (noon)
Design point irradiance	900 W/m2
Layout;	Surrounding
Heliostats area	10.4 m x 10.4 m
Receiver elevation	126 m from the heliostat pivot point.

4.1. Field efficiency optimization

In order to obtain the best field for each scenario for the field efficiency objective function, two tasks have to be performed. First, for each heliostat layout generation algorithm, the field that maximizes the field efficiency is obtained by the optimization process defined in the Section 3 in order to avoid meaningless comparisons. After obtaining these fields, the algorithm with the highest efficiency is selected in a second step. In the optimization process the heliostat reflectivity and the losses related to spillage have not been taken into account, for this reason the results cannot be compared with real plants.

Figure 3 shows the fields obtained by the optimization process for each algorithm using maximized field efficiency as objective function. As we can see in this figure, we obtain a north field as a results of optimization because the annual energy provided by these nodes are higher that others placed south with respect to the tower. Table 3 shows the main values of the fields for the 100 MWth scenario, the annual energy is the energy provided for all the heliostats in the field to receiver. The field obtained using Fermat spiral is the field with the higher efficiency. In these fields the losses related to blocking are higher in the dense radial staggered algorithm because the distance between heliostats is smaller than other algorithms. However, for the same reason the atmospheric attenuation losses are lower.

Table 3. 100 MWth heliostat field

Algorithm	Parameters	Number of heliostats	Efficiency (%)	Annual Energy (GWth)
Dense radial staggered	dsep=8	1205	0.711	203.555
Campo	dsep=3; fbref=0.9	1110	0.751	197.976
Graphical method	dsep=0.7	1124	0.741	197.996
DELSOL	Nrad=40; expansionFactor=1.3; gapBetweenZones=19	1106	0.750	196.986
Fermat spiral	a=1.25; b=0.825	1110	0.752	198.413

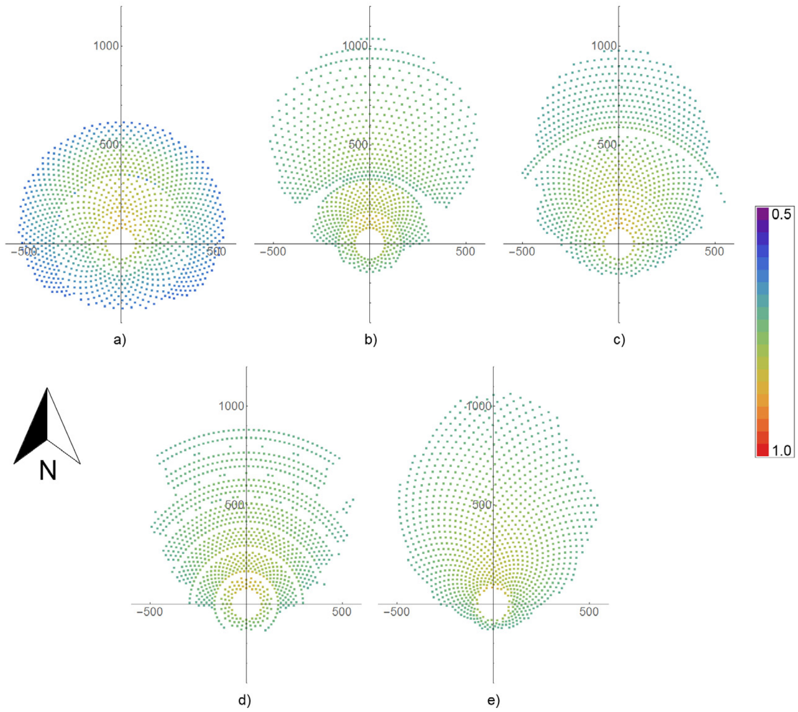

Fig. 3. Heliostat field layout obtained by optimization for 100MWth scenario. a) Dense radial staggerd, b) Campo, c) Graphical method, d) DELSOL and e) Fermat spiral

For the second scenario (120 MWth field), the best field is also obtained using Fermat spiral as shown in the Table 4. Figure 4 shows the optimized field for each algorithm for the fields of 120 MWth at the design point.

Table 4. 120 MWth heliostat field

Algorithm	Parameters	Number of heliostats	Efficiency (%)	Annual Energy (GWth)
Dense radial staggered	dsep=10	1513	0.689	247,850
Campo	dsep=3; fbref=0.9	1350	0.741	237.810
Graphical method	dsep=0.0	1368	0.731	237.633
DELSOL	Nrad=36; expansionFactor=1.3; gapBetweenZones=13	1344	0.741	236.534
Fermat Spiral	a=1.25; b=0.825	1354	0.742	238.873

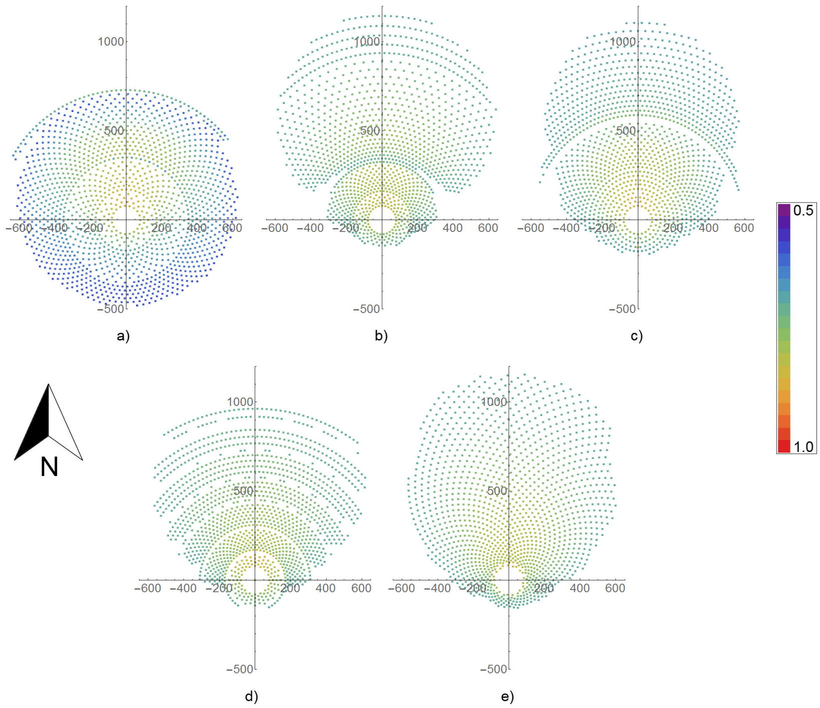

Fig. 4. Heliostat field layout obtained by optimization for 120MWth scenario. a) Dense Radial Staggerd, b) Campo, c) Graphical Method, d) DELSOL and e) Fermat Spiral

Finally, we can show the results of the third scenario, a plant of 150 MWth at the design point. These results are presented in the Table 5 and Figure 5.

Table 5. 150 MWth heliostat field

Algorithm	Parameters	Number of heliostats	Efficiency (%)	Annual Ennergy (GWth)
Dense radial staggered	dsep=8	1974	0,661	310.059
Campo	dsep=3; fbref=0.9	1721	0,730	298.029
Graphical method	dsep=0.7	1745	0,717	297.379
DELSOL	Nrad=35; expansionFactor=1.3; gapBetweenZones=16	1720	0,727	297.041
Fermat spiral	a=1.0; b=0.85	1727	0,729	299.180

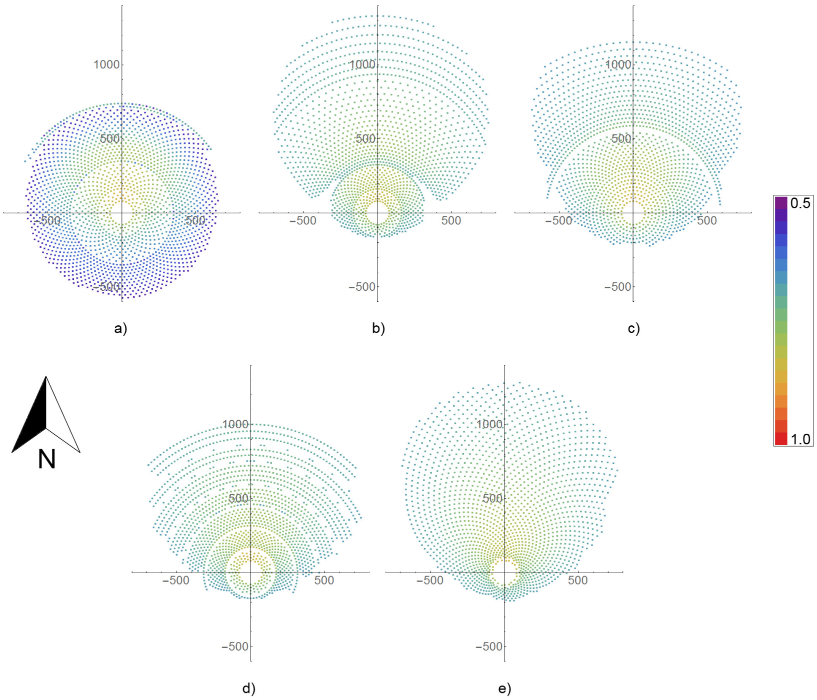

Fig. 5. Heliostat field layout obtained by optimization for 150 MWth scenario. a) Dense Radial Staggerd, b) Campo, c) Graphical Method, d) DELSOL and e) Fermat Spiral

After analyzing the results, the annual energy obtained with the graphical method algorithm is similar to the energy obtained by other algorithms. However, the efficiencies are lower compared with the others. The graphical method uses more heliostats to obtain the same annual energy, and therefore, the fields are less efficient than the others.

On the other hand, DELSOL creates efficient layouts with less heliostat number. For this reason, the annual energy provided by the field heliostats is lower compared to other algorithms.

4.1.1. Annual energy vs field efficiency

The main goal of this study is to find a heliostat field layout with the higher performance. As mentioned in Section 3, we need to solve a multi-objective optimization problem, maximizing the annual energy of the field and the field efficiency. Because this objective functions are in conflict, it is impossible to obtain a unique solution. For this reason a Pareto front is created for each algorithm.

The BSA algorithm allows finding different solutions in the efficient region. This algorithm solves the optimization problem using the method of ε-constraints. For this study 5 regions have been analyzed, ε = 0.5, 0.55, 0.6, 0.65 and 0.7 is solved.

After calculating the efficient region for all the algorithms, a comparison between these regions is carried out. With this aim, in the end, all the regions are mixed in a unique chart. The Figure 6, summarizes the Pareto fronts build for each of the algorithms analyzed for the 120MWth scenario. This figure shows that the field's annual energy obtained by the graphical method algorithms is lower than in other algorithms for the same efficiency. Although there are some cases where the annual energy is higher (efficiencies between 0.685 and 0.715), for the same efficiencies the rest of the algorithms obtain better results.

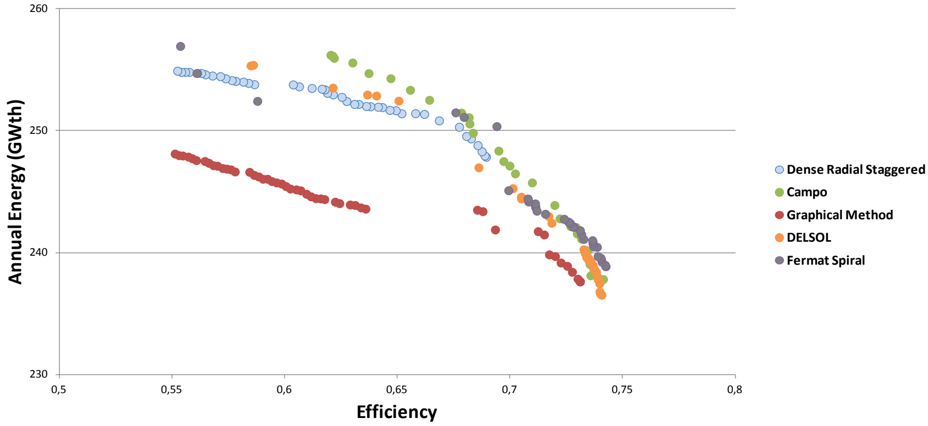

Fig. 6. Analyzed algorithms Pareto front for 120 MWth scenario.

The main conclusion for the dense radial staggered field is that the maximum field efficiencies obtained for this fields presents a low value, near to 0.684. The high number of heliostats needed by this algorithm to achieve the same annual energy is the reason that these fields could not reach high efficiency values.

DELSOL behavior is not as good as the Campo and Fermat spiral algorithm, but this behavior is better than previously mentioned algorithms, dense radial staggered and the graphical method. However, for high annual power fields, the differences with Campo and Fermat spiral are reduced.

Fermat spiral and Campo algorithms alternate as best solution for the scenario of 120 MWth at different points. For high efficiencies (about 0.74) the best option is the Biomimetic algorithm which provides higher power. But to reach higher annual energy fields, Campo solves better the problem (efficiency around 0.725). There are some particular cases, located between efficiencies 0.675 and 0.695, where the Fermat spiral gets more power by providing a better solution to the problem.

Figure 7 shows the same study for 100 MWth and 150 MWth scenarios. As can be seen, the fronts of the algorithms have a similar pattern as in the previous analyzed scenario.

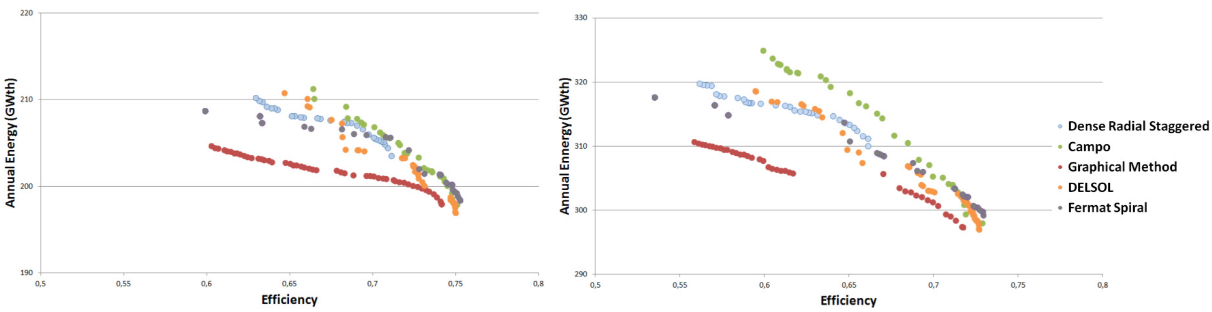

Fig. 7. Analyzed algorithms Pareto front for a) 100 MWth and b) 150 MWth scenarios.

The main difference of these results is the behavior of the DELSOL algorithm. For small fields DELSOL can be considered a good alternative to generated heliostat fields. For fields with high design point power, the behavior of Campo is clearly the best option, except for high efficiency fields.

5. Conclusions

The results presented in this paper show a methodology for the optimization and comparison of heliostat field layouts generated by different algorithms. Taking into account the values and charts presented, the Fermat spiral pattern and Campo are the algorithms to build the fields with greater performance in terms of field efficiency and field annual energy vs. field efficiency. The solutions obtained with the graphical method and the dense radial staggered method are not as good as other solutions because for a particular field efficiency, higher annual energy can be achieved using other algorithms. DELSOL could be a good option for some cases.

These results can be observed in both comparisons, because the most efficient fields for the three scenarios are the mentioned ones and Pareto front charts indicate that they are the best algorithms to obtain high efficiencies and high annual energy in the receiver.

The studies performed have taken into account some concrete scenarios, with the same type of field (surrounding fields), the same heliostats, tower and location. For this reason, another study is needed to analyze if these conclusions are valid for other scenarios. Future comparisons using the same methodology helps the designers to start working in the optimization of the fields using the most promising algorithm for the location and field characteristic needed.

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